A Reflectarray Antenna Using Crosses and Square Rings for 5G Millimeter-Wave Application

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***Abstract*—A reflectarray antenna of 441 unit-cells with dimensions of 112.5 mm x 112.5 mm is proposed in this paper. The unit-cell consists of a cross and a square ring. The reflectarray is illuminated by a horn antenna at the center-feed and 25 degrees offset-feed with the 3 GHz bandwidth (from 26.5 GHz to 29.5 GHz) for N257 band/5G. The shadow area of the reflectarray antenna is improved by the 25 degrees offset-fed structure with a peak gain of 26.4 dBi satisfied with the 5G base station antenna requirement.**

Keywords—Reflectarray, cross, square ring, center-feed, offset-feed, 5G, millimeter waves.

I. INTRODUCTION

The reflectarray antennas were introduced in the early 1960s [1], which was a set of waveguides. However, until the 1980s, it was paid attention more due to the advance of printed circuit technology. From that day forward, microstrip reflectarray becomes more popular. Compared to conventional reflectors, it has advantages, such as flat profile, low mass, and low cost. However, the reflectarray antenna also has a limitation inherited from microstrip antennas: a narrow bandwidth (around 3 %) [2]. Many methods are applied to improve their bandwidths, such as multi-layer configurations [3] and multi resonant elements [4], [5]. Several reflectarray configurations are used widely in the microwave [6] and millimeter-wave bands [7], especially in satellite communication. They also demonstrate excellent performances of directivity and beamforming capability [8], [9] like phased array antennas despite not utilizing phase-shifting networks. For 5G application, high data rate, low latency, and wide bandwidth requirements are just achievable at millimeter-wave bands. However, designing millimeter waves 5G base station antenna is a big challenge for researchers due to a large number of phased array elements (up to 256 elements) [10]. Phased array antennas with digital beamforming become more bulky, complicated, and high cost because each antenna element is always attached to a DAC, an ADC, and RF processing blocks. Meanwhile, phased array antennas with analog beamforming have a significant loss in feed networks, which decreases the gains of these antennas. In recent years, a few reflectarray antennas were designed for mmWaves/5G applications as a solution to overcome these limitations. In 2017, Shiyu Zhang [11] designed a 120 mm x 120 mm reflectarray from dielectric material using 3D printing technology. It achieved a peak gain of 28 dBi at 30 GHz and -1 dB bandwidth of about 10%. In that year, Rania R. Elsharkawy [12] also proposed a reflectarray comprising microstrip octagonal unit cells with aperture dimensions of 160 mm x 160 mm. The achieved peak gain of this antenna is 31.39 dBi, and its -1 dB bandwidth is 13.87%. In 2018, Yun Hu [13] presented a folded reflectarray antenna with dimensions of 140 mm × 108 mm. It is fed by series substrate integrated waveguides. It attainted a peak gain of 25.9 dBi at 42 GHz and a -3 dB bandwidth of 10%. In 2020, S. Costanzo [14] proposed a reflectarray antenna using two pairs of miniaturized fractal patches with the aperture dimensions of 140 mm x 140 mm and a peak gain of 25.7 dBi at 32 GHz and -1 dB bandwidth of 2.4%.

In this work, the authors describe a reflectarray antenna, including 441 elements with dimensions of 112.5 mm x 112.5 mm. The reflectarray antenna operates at 5G millimeter-wave band N257 (26.5 GHz to 29.5 GHz) [15]. The reflectarray element is combined by a square ring [16] and a cross [17] to create a broadband reflectarray antenna that satisfies the bandwidth requirements of the 5G network. Two feeding structures for the reflectarray antenna are demonstrated: center-feed and offset-feed. The paper is divided into five sections. Section 2 shows the model and specifications of the reflectarray unit-cell. Section 3 presents designing two reflectarray configurations with feeding structures: center-feed and offset-feed. Simulation results of both reflectarray antenna configurations designed are depicted in section 4. Section 5 is the conclusions.

II. REFLECTARRAY UNIT-CELL

The model of the unit-cell comprising a cross inside and a square ring outside is demonstrated in Figures 1a and 1b, which is an improved cross to satisfy a wide frequency range from 26.5 GHz to 29.5 GHz [18]. The equivalent circuit of an unit-cell is shown in Figure 1c. The first circuit comprising L_1, C_1, and C_{gd1} presents for the ring while the presentation of the cross is the second resonant circuit, including L_2, C_2, and C_{gd2}. The capacitances C_1 represent the coupling between the square ring and the cross meanwhile C_2 shows the relation between unit cells beside; The cross and the square ring act as inductances L_1 and L_2, respectively; C_{gd1} is the capacitance between the cross and the ground plane, and C_{gd2} is the capacitance between the ring and the ground plane. As described in [19], two resonant frequencies of the equivalent circuit are calculated by the (1) and (2). f_1 *is* the resonant frequency of the cross; f_2 is the resonant frequency of the square ring. Therefore, changing the length of the cross and the length of the square ring lead to an adjustment in the resonant frequencies f_1 and f_2, respectively.

The unit-cell is etched on a ROGER RT5870 substrate with permittivity $\varepsilon_r = 2.3$, and its optimized dimensions are shown in Table 1. In reflectarray design, the phases of elements are popularly used to compensate for the phase deviations due to different distances from the feed to the elements. By varying the size of elements, the reflection phases and the reflection coefficients are achieved and plotted in Figure 2. The parallel waveguide simulator is used to analyze this unit-cell [19], [20]. It can be seen that the reflection coefficients of variable size unit-cells are changed from -0.22 dB to -0.009 dB, and their phase ranges are adjusted more than 530°.

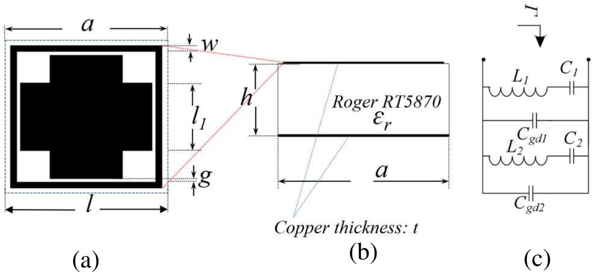

Fig.1. Model of the unit-cell (a) side view, (b) front view, (c) equivalent circuit

TABLE I. SIZES OF THE UNIT CELL

l	*l₁*	*w*	*g*	*a*	*h*	*t*
4.49	2.13	0.37	0.22	5.35	1.575	0.035

Unit: mm

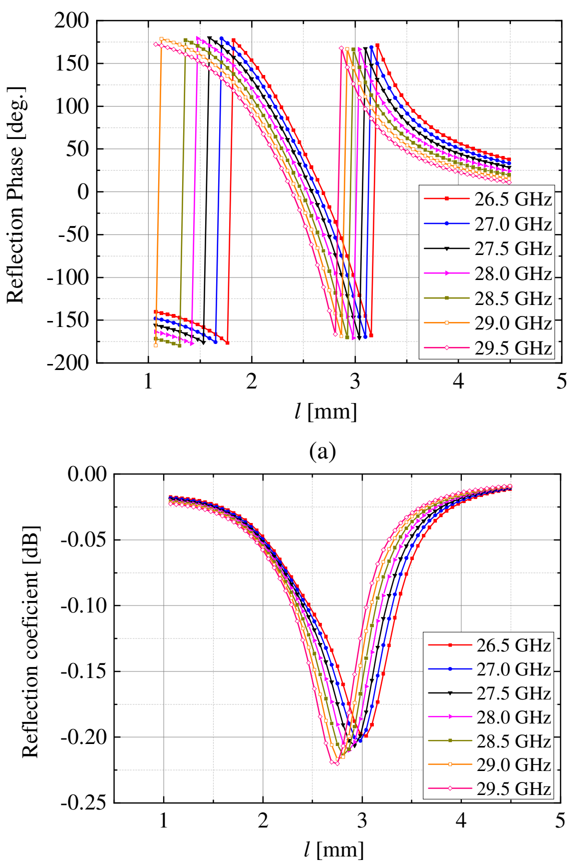

Fig. 2. The reflection phases (a) and the reflection coefficients (b) of variable size elements

$$f_1 = \sqrt{\frac{1}{4\pi^2 L_1 (C_1 + C_{gd1})}} \quad (1)$$

$$f_2 = \sqrt{\frac{1}{4\pi^2 L_2 (C_2 + C_{gd2})}} \quad (2)$$

III. REFLECTARRAY CONFIGURATION DESIGN

In this work, a conical horn is selected as a feeder for reflectarray antennas. The horn aperture is approximately 17% of the reflectarray antenna apertures proposed to minimize the feed blockage. The peak gains of the feeder are around 14 dBi, equivalent to $q = 6$ in the radiation pattern formula (3) [21].

$$U_f(\theta,\phi) = \begin{cases} \cos^{2q}(\theta) & (0 \le \theta \le \frac{\pi}{2}) \\ 0 & elsewhere \end{cases} \quad (3)$$

The reflectarray is constructed from 441 elements that are arranged with a distance of half-wavelength. Both center-fed and offset-fed structures are designed and simulated, which allows a comparison of their performances. They also have limitations: the center-fed reflectarray has a feeding blockage while the offset-fed structure encounters an oblique effect. The geometrical structure of the reflectarray antenna is shown in Figure 3 [19]; The phases of elements are calculated by (4) [19]:

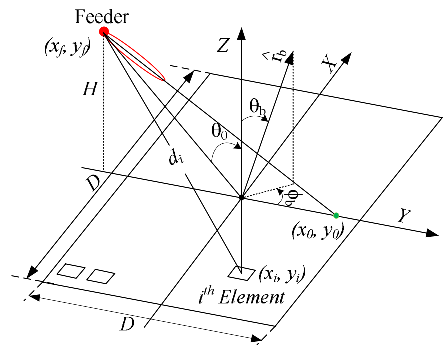

Fig. 3. The geometrical parameters of a planar reflectarray antenna

$$\begin{cases} \phi(x_i, y_i) = -k_0 d_i + \phi_R(x_i, y_i) \\ \phi_R(x_i, y_i) = -k_0 \sin\theta_b \cos\varphi_b x_i - k_0 \sin\theta_b \sin\varphi_b y_i \end{cases} \quad (4)$$

where k_0 is the free space wavenumber; d_i is the distance from the feeder to the i^{th} element, $\phi_R(x_i, y_i)$ is the phase of the i^{th} element that creates a beam at (θ_b, φ_b). In this work, just a beam at ($\theta_b = 0$, $\varphi_b = 0$) is radiated, therefore:

$$\begin{cases} \phi_R(x_i, y_i) = 0 \\ \phi(x_i, y_i) = -k_0 d_i \end{cases} \quad (5)$$

A. Center-Fed Reflectarray Structure

For the center-fed structure, only the height of feeder - *H* is needed to calculate. The *H* parameter primarily depends on the reflectarray antenna aperture, which is similar to the focal length of conventional reflectors. With the dimensions of the proposed reflectarray antenna, *H* is calculated and shown in Figure 4a. It is noticed that the optimal *H/D* ratio in for this structure is 0.77 (*H=86.625 mm*), which is expected to achieve an aperture efficiency of 77%. The reflection phases for elements of this reflectarray are also determined by (5) and Figure 3 and shown in Figure 4b. The sizes of all elements in the center-fed reflectarray and the position of the horn are demonstrated in Figures 4c, 4d.

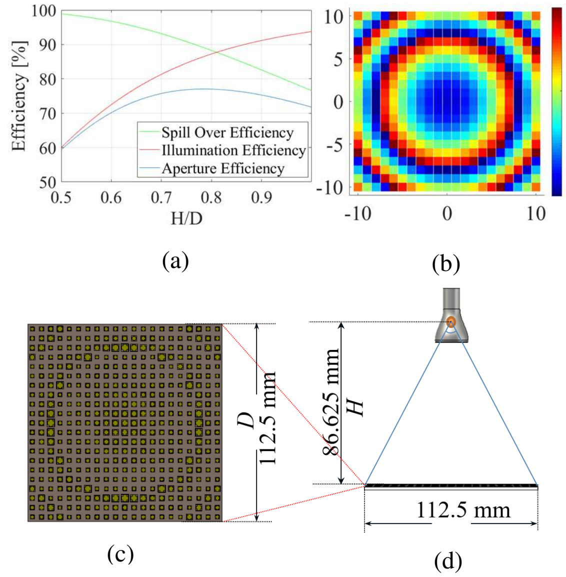

Fig. 4. The aperture efficiency (a) and the phase distribution (b), the front view (c) and the side view (d) of the center-fed reflectarray

B. *Offset-Fed Reflectarray Structure*

The offset-fed reflectarray antenna is designed by three parameters shown in Figure 3 (H, θ_0, and (x_0, y_0)).

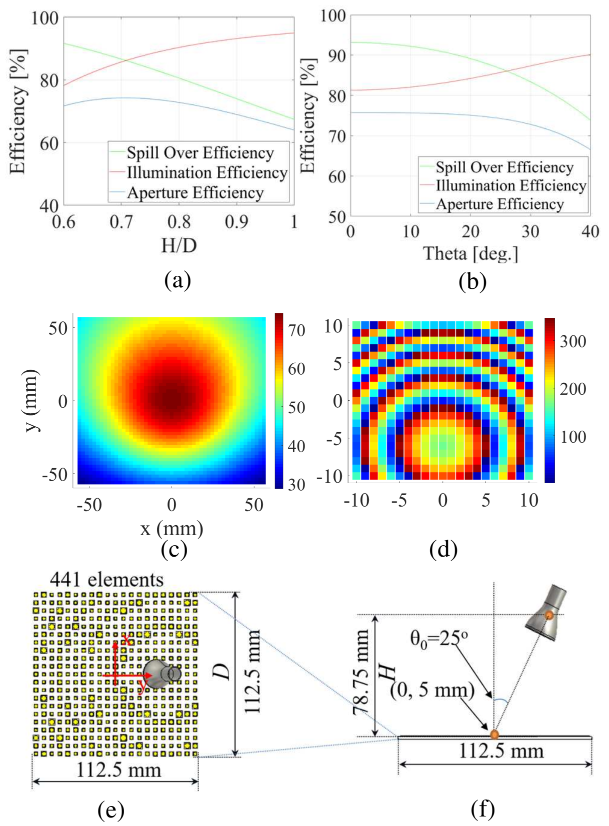

Fig. 5. The Aperture efficiency of the offset-fed reflectarray antenna related to three parameters: the ratio between the reflectarray aperture and the height of feeder (a), the angle between the line connected from the feeder to the center of the reflectarray and z-axis (b), the location of the feeder directs to (c); The element phase distribution of the offset-fed reflectarray (d); The configurations of the offset-fed reflectarray: the front view (e) and the side view (f)

H is the height of the feeder. θ_0 is the angle between the line connected from the feeder to the center of the reflectarray and the z-axis. (x_0, y_0) is the location on the reflectarray that the main beam of the feeder directs to. The aperture efficiency of antenna related to each parameter are illustrated in Figures 5a, 5b, 5c. As can be seen, the optimal H/D, θ_0, and (x_0, y_0) are 0.7, 25°, and (0, 5). Those values are expected to keep the aperture efficiency of around 74% and reduce the feeding blockage. Figure 5d shows the element reflection phases of the reflectarray, and the Figures 5e, 5f present the configuration of the offset-fed reflectarray antenna.

IV. Simulation Results

Figures 6 and 7 present the simulated radiation pattern and the bandwidth performance of two antenna configurations in the band from 26.5 GHz to 29.5 GHz. The detailed results are listed in Table 2. The effect of oblique angles of incidence [19] leads to diminishing the gain of the offset-fed antenna so that the gains of the center-fed structure are always more than from 0.5 dB to 1.4 dB, compared to the offset-fed reflectarray structure. From Table 2, the general trend of gains is decreased to the sides of the frequency beacause the phase errors of elements in the reflectarrays are smaller in the middle of the frequency band or the size of all elements is designed at the center frequency (28 GHz). The aperture blockage effects are obviously shown as the angle of the radiation patterns are expanded, or the sidelobe levels increase at the location of the feeder (within theta from 83° to 97°) for the center-fed configuration. It could be explained that the electromagnetic waves radiated from the reflectarray are reflected and diffracted to other directions at the feeder surfaces. For the offset-fed reflectarray, the effects of aperture blockage just cause the slightly dissymmetrical radiation pattern on the left side. As is illustrated in the figure, the sidelobe levels of the offset-fed structure are also more stable than the center-fed structure, 4.1 dB compared to 7.3 dB. Figure 7 depicts that the offset-fed antenna has a slightly better bandwidth performance when compared to that of the center-feed antenna (0.9 dB vs. 1.1 dB), although it achieves better gains than offset-fed one.

Table 3 shows the comparison between this work and related works. Similar to these designs, the peak gain of the proposed reflectarray antenna corresponds to the ratio between the aperture area and the square root of the wavelength. The sidelobe level and the bandwidth of the proposed antenna show good performances. Hence, this antenna could be a potential candidate for 5G base stations.

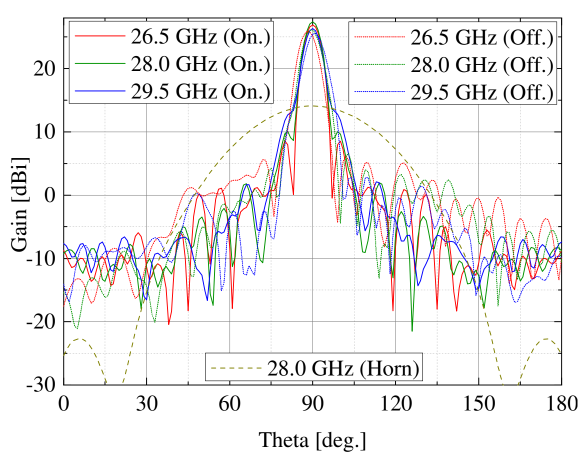

Fig. 6. The radiation pattern of the reflectarray antennas

TABLE II. GAIN, SIDE LOBE LEVEL, AND HALF POWER BEAMWIDTH OF THE REFLECTARRAY ANTENNAS

Frequency (GHz)	Center-fed reflectarray			Offset-fed reflectarray		
	Max. Gain (dBi)	Sidelobe level (dB)	Half power beamwidth (°)	Max. Gain (dBi)	Sidelobe level (dB)	Half power beamwidth (°)
26.5	26.9	- 18.3	6.0	25.5 (89°)	-19.7	6.4
27	26.5	- 18.9	5.9	25.9 (89°)	-21.1	6.0
27.5	27.1	- 18.9	5.8	25.9 (89°)	-20.3	6.0
28	27.4	- 17.3	5.9	26.2 (90°)	-21.7	6.2
28.5	26.9	- 18.4	5.8	26.4 (90°)	-25.2	6.1
29	27.3	- 16.9	5.6	26.2 (91°)	-23.2	5.9
29.5	26.3	-24.2	6.0	25.7 (91°)	-23.8	6.1

TABLE III. A COMPARISON OF THIS WORK AND RELATED WORKS

	Reflectarray in [14]	Reflectarray in [12]	Reflectarray in [11]	Reflectarray in [13]	This work (Off-set feed)
Material/number of layers	Planar/1 layer	Planar/1 layer	Dielectric	Planar/folded	Planar/1 layer
Central Freq. [GHz]	32	28	30	42	28
H/D	1.2	1.5	1		0.77
Surface area/λ^2	75.8	225	144	297	110
Peak gain [dBi]	25.7	31.39	28	25.9	26.4
Sidelobe level [dB]	Not given	-23.6	-25.5	-13	-25.2
1 dB gain bandwidth [%]	2.4	13.87	10	10 (-3 dB bandwidth)	10.7

H/D: The ratio between the distance from feeder to the reflectarray surface and the length or the diameter of the reflectarray.

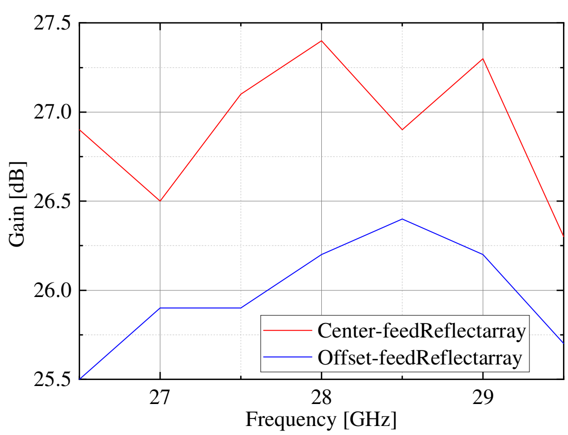

Fig. 7. Gain against frequency for the designed reflectarray antennas

V. CONCLUSIONS

Broadband reflectarray antennas comprised crosses and square rings are designed and examined at the N257/5G band (26.5 GHz to 29.5 GHz). Two feeding methods are also designed and simulated. The results show the peak gain attained is 27.4 dBi for center-fed reflectarray antenna and 26.4 dBi for the antenna with offset-feed. The bandwidth performance of the offset-fed reflectarray antenna is improved when compared to the center-fed one (0.9 dB to 1.1 dB). The flatter sidelobe levels of offset-fed structure are observed.

ACKNOWLEDGMENT

This research is funded by the Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 102.04-2018.08.

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